Mechanisms of Fluid-Mud Interactions Under Waves

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LONG-TERM GOALS

The goals of this project are to investigate the mechanisms for wave dissipation in the presence of bottom mud. There are a variety of possible mechanisms for the decay of wave energy as waves propagate over mud; however, they have not all been validated in the field nor quantified in terms of their relative importance and damping rates in the field or the laboratory. Further new mechanisms may be found. Implementation of these mechanisms into numerical models provides the ability to infer from the sea surface the nature of the bottom material.

OBJECTIVES

We are measuring wave damping due to mud off the coast of Louisiana, quantifying the dynamics of the bottom mechanisms responsible for the dissipation of wave energy. We are examining different mechanisms for the damping of wave energy by bottom mud in the laboratory and through the use of theoretical and numerical models. These damping mechanisms include the direct forcing of the mud by the wave-induced bottom pressure and velocities; indirect forcing through nonlinear surface wave effects (including wave groups); resonant forcing of interfacial waves at the water/mud interface; damping and shear instabilities in the lutocline; and large scale broadband mechanisms that involve a complex sea state and a combination of the above mechanisms.

APPROACH

The approach is three-pronged: a field effort, involving experiments within a mud patch offshore the coast of Louisiana; a laboratory effort, involving examining the above mechanisms in a controlled environment; and a theoretical and numerical approach, with the ultimate objective of providing numerical models that include wave damping over mud.

The field work consists of three field campaigns (2007 pilot study; 2008 main field experiment, 2010 planned experiment) of wave and bottom measurements. The experiments involve the use of a bottom mounted quadrapods that supports acoustical instruments to measure the horizontal and vertical

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structure of the velocity and concentration of sediment at the bottom. In addition, a surface buoy provides atmospheric measurements, and two tripods at the seaward and landward ends of the experimental area provide estimates of the directional wave spectrum and energy flux into the study area. These tripods also have acoustic backscatter devices to measure the thickness and mud layer concentrations. In addition, cores of the seabed have been taken to determine recent depositional history, porosity, and mixing depth.

Laboratory experiments of waves over muds are being made in two experimental facilities. The first is a shaker table that supports a water/mud tank. This small-scale tank is oscillated to excite wave motion and then stopped so that the decay of the wave motion can be measured. The second is an 18m long wave tank outfitted with a 10 m long, 10 cm deep mud patch within a false bottom. A string of acoustic and wire wave gages measure the decay of the waves down the tank.

A large-scale phase-resolved Bottom Mud Wave numerical simulation (BMW) was developed and applied to investigate various mechanisms of fluid-mud interactions under surface waves. BMWs have been developed, based on the integration of the theoretical studies, direct numerical and large-eddy simulation developments, tank measurements, and field experiments conducted in this project, for the prediction of wavefield evolution over muddy bottom and topography. BMWs utilizes a direct phase-resolved simulation for broadband nonlinear wavefield evolution over a horizontal length scale of $O(100\ \lambda)$ (~10km) per dimension by integrating through closure modeling wave transformation and dissipation mechanisms obtained at smaller scales ($O(\lambda)$) via asymptotic theory and DNS/LES, cross-calibrated with measurements.

WORK COMPLETED

Field: Two field experiments have been completed and data are being analyzed. Both shipboard measurements (bottom samples) and instrumented array experiments have been carried out.

Theory and Modeling: A computational capability, BMWs, for direct simulation of large-scale nonlinear wave-mud interactions has been developed and applied. A dissipation model accounting for direct wave interactions with bottom mud with various non-Newtonian properties has been developed, parameterized, and integrated into BMWs. A theory for nonlinear evolution of small-amplitude waves over a thin non-Newtonian mud layer has been developed. A direct numerical simulation (DNS) capability for understanding turbulent interactions of waves with non-Newtonian fluid mud has been developed.

Laboratory: Two experimental series are underway in both the wave tank and a shaker table apparatus. A catalog of the rheology of kaolinite clay has been completed.

RESULTS

Shipboard measurements: The shipboard measurements in conjunction with the field wave damping experiments were carried out to provide information on spatial and temporal variability of seabed characteristics (grain size, porosity, mixing depth and Be-7) and to provide snapshots of cross-shelf suspended sediment and stratification in the water column.

Analysis of sediment-core data from 2007 and 2008 document the occurrence of recently deposited, high-porosity sediments that are highly mobile over monthly timescales (Figure 1). The combined observations suggest that sediment is first delivered from fluvial sources to the east following peak river flow in early spring, and then deposited across a wide region extending 10-15 km from the shore.

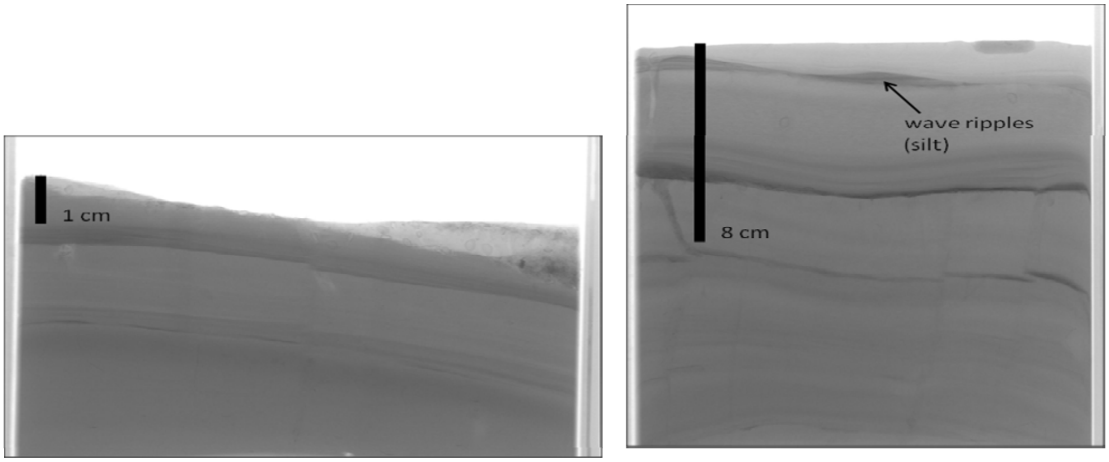


Figure 1. X-radiographic images from sediment cores taken near the middle pod in February 2008 (left, core BC4-0208), and March (right, BC4-0308), showing penetration depth of detectable Be-7 (as black bar) in each core, and wave-rippled silt in the March core. The local net sediment accretion evident from February to March equates to deposition of roughly 39 kg m^{-2} of dry sediment over the intervening month.

In-situ measurements of seafloor characteristics and wave energy loss: We are analyzing the data collected in the 2008 field program from an array of three tripods deployed on the Western Louisiana shelf from February 13th to April 10th. The outer (9 m water depth) and inner (5 m water depth) tripods contained an upward looking Nortek AWAC (acoustic wave and current) profiler to measure waves, an ABS to measure profiles of suspended sediment and fluid mud concentration, an ADV to measure near bed velocities, and an OBS5 sensor to measure sediment concentration. The 5-m site also contained downward aimed pulse coherent ADCP. The central (7 m water depth) tripod contained the same instrumentation along with a vertical array of three ADVs and an array of downward aimed pulse coherent Doppler sonars to image waves on the mud-water interface. A suite of meteorological measurements was also collected near the central site.

Acoustic backscatter profiler (ABS) measurements showed deposition of 20 cm in 5- to 7-m water depths after each of three wave events with wave heights of near 2 m on the 9 m isobath (Figure 2). While total wave energy dissipation as measured by the AWACs was greatest during the high energy periods, the spatial attenuation rate (Dissipation/Energy Flux, with dimensions of an inverse length scale) was largest after the wave events, as the recently deposited mud layer consolidated from 20 cm to 10 cm thickness (after each of the green vertical lines in Figure 2). The ABS data also showed waves on the lutocline with heights ranging from 10 cm during periods of high total wave energy dissipation to 2 cm during periods of maximum attenuation rate (see Figure 3 and 4 for an example of these waves). Analysis and direct measurements of the wavelength of mud-water interface waves from the spatial array indicate these waves have short wavelength (~3 to 4 m) relative to the surface waves (~ 60 m), but oscillate at the same frequency (Figures 3 and 4).

Data from a 20° off vertical Doppler beam combined with an adjacent vertical beam was also used to measure the vertical structure of horizontal velocity. The velocity profile data (Figure 5) shows that during periods of maximum wave attenuation, the wave boundary layer expands to fill the entire mud layer, consistent with theory that suggests attenuation should be maximized when the velocity boundary layer thickness ($\delta = \sqrt{2\nu/\omega}$) is approximately equal to the mud layer thickness (h_m), i.e. $h_m/\delta = 1.4$. Models based on two-layer theory (e.g. Dalrymple and Liu, 1978) can fit the measured velocity data with a viscosity of 0.01 m^2/s, four orders of magnitude greater than clear water. The spatial attenuation predicted from two layer theory is 0.001 m^{-1}, which a factor two greater than the measured attenuation from the 9m site to the 5 m site of 0.005 m^{-1}. Reasons for the difference are being explored.

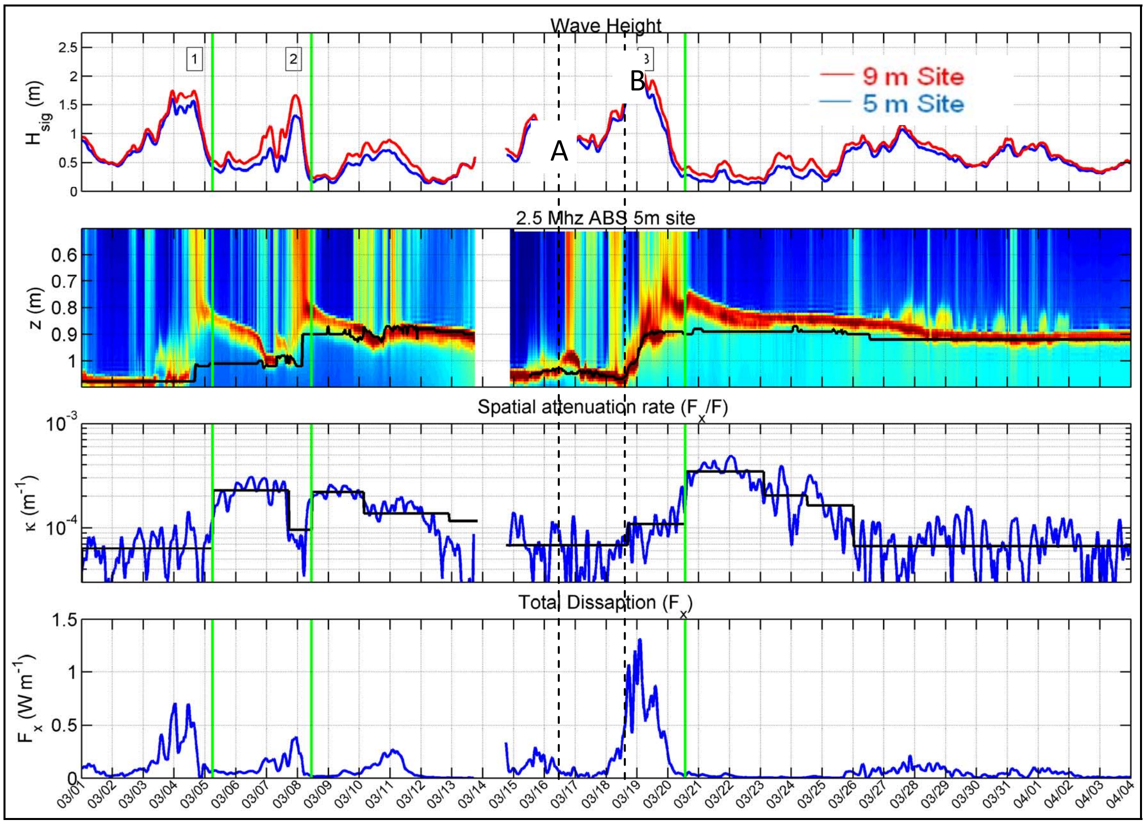


Figure 2. a) Time series of $H_{1/3}$ from the 5 m (blue) and 9 m (red) isobath sites. The three wave events with $H_{1/3}$ > 1.5 m are labeled 1, 2 and 3. b) Burst averaged 2.5 MHz ABS data with the consolidated mud bottom, calculated from the 1 MHz ABS data shown as a black line. The color is proportional to backscattered intensity, corrected to account for sediment attenuation in the water column. c) Attenuation F_x/F calculated from the 9 m and 5 m site (blue) and a stepwise low pass fit (black) d) The amplitude of the lutocline waves ($h_{0,1/3}$, blue) and the thickness of the mud layer (h_m,red). The vertical green lines indicate the beginning of period of high normalized attenuation coincident with recently deposited mud layers.

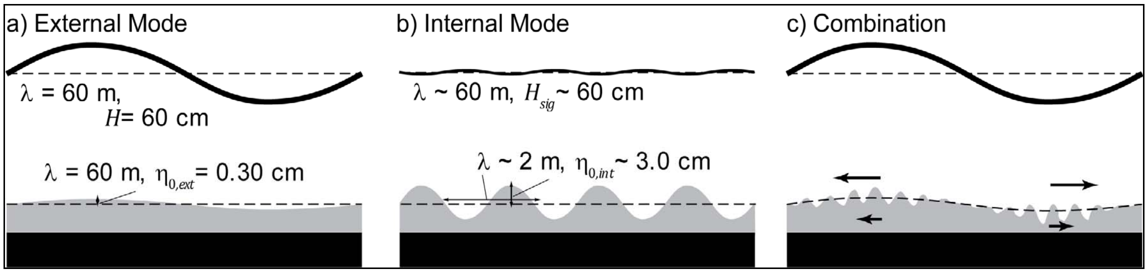


Figure 3. Schematic diagram of the two layer system showing: a) the external wave mode with the same frequency and wavelength for both the air-water and water-mud interface waves; b) the internal wave mode with the same frequency, but much shorter wavelength for the water-mud interface waves, and c) the combination of the two. The arrows in panel c) indicate shear across the mud water interface, which could lead to a shear instability mechanism to generate the internal mode waves in each half cycle of the surface wave. These internal waves dissipate rapidly with imaginary and real wave numbers of a similar magnitude and remove energy from the surface waves.

Analysis and Modeling: Three different modeling efforts are underway. The first focuses on the non-Newtonian bottom boundary layer and the interfacial coupling at the water-mud interface, which provides a detailed description of the flow velocity field, identifies key vortical structures in the non-Newtonian fluid boundary layer, elucidates the formation and evolution processes of the vortices. The results were validated against the theoretical prediction by Dalrymple & Liu (1978), the measurements by Sakakiyama & Bijker (1989), and the simulation by Zhang & Ng (2006).

A second approach is a theoretical study for predicting the effects of fluid mud on waves in nearshore waters with emphasis on two realistic features of fluid mud in coastal waters: the viscoelastic rheology and the small thickness of the mud layer. The model shows that at the leading order in wave steepness, mud is forced to move passively by the hydrodynamic pressure from the surface waves above, resulting in viscous dissipation within the fluid mud. Over very long distance, mud dissipation gradually extracts energy from waves above and alters the leading-order waves above by creating a complex shift of wavenumber which amounts to attenuation of wave amplitude and change of wave length.

The third approach are direct phase-resolved bottom mud wave simulations (BMW). The method is capable of simulating the evolution of broadband waves traveling over long shoaling. As an illustrative study, BMWs are performed for conditions corresponding to recent field observations of significant wave spectral transformation over a sloped muddy Louisiana shelf. Comparisons of the direct simulations by BMWs and the field experiments of Elgar & Raubenheimer (2008) in Figure 6 indicate that the bottom mud properties on the Louisiana shelf more closely resemble those in Hangchow Bay reported by Huhe & Huang (1994), and are significantly less dissipative than the mud of Jiang & Mehta (1995).

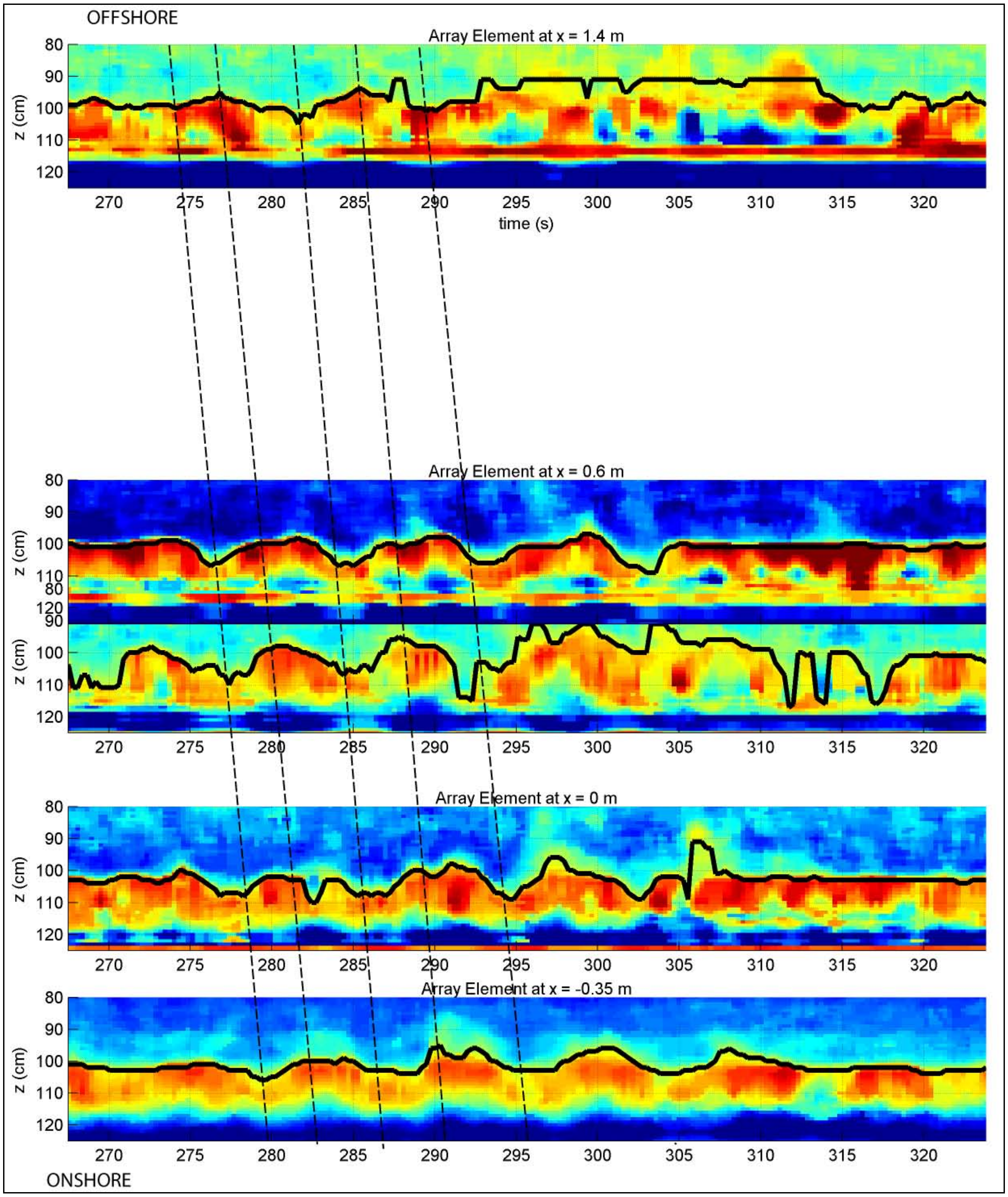


Figure 4. Backscatter amplitude from the linear array of downward aimed pulse coherent Doppler profilers. The dashed lines represent phase speed (Δx/Δt) of the waves across the array. For this data burst the phase speed is 0.25 m/s. Combining this with a wave period of 7 s yields a wavelength of 1.75 m.

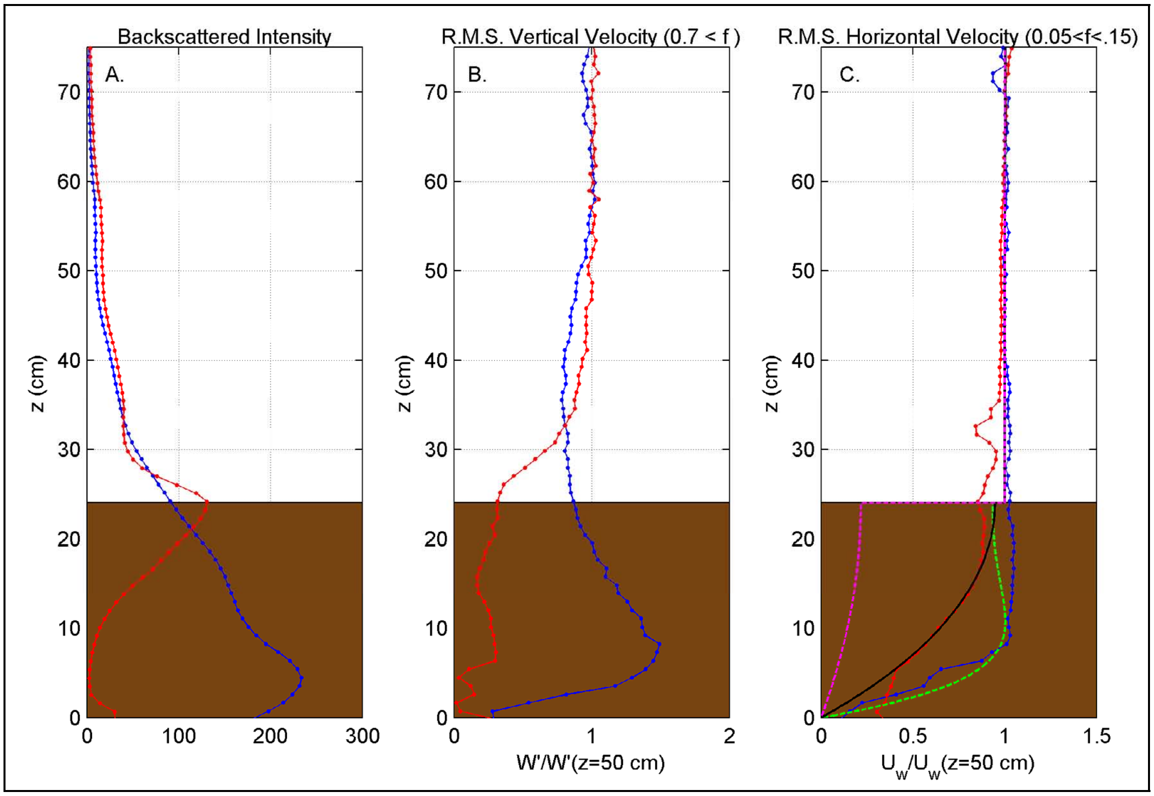
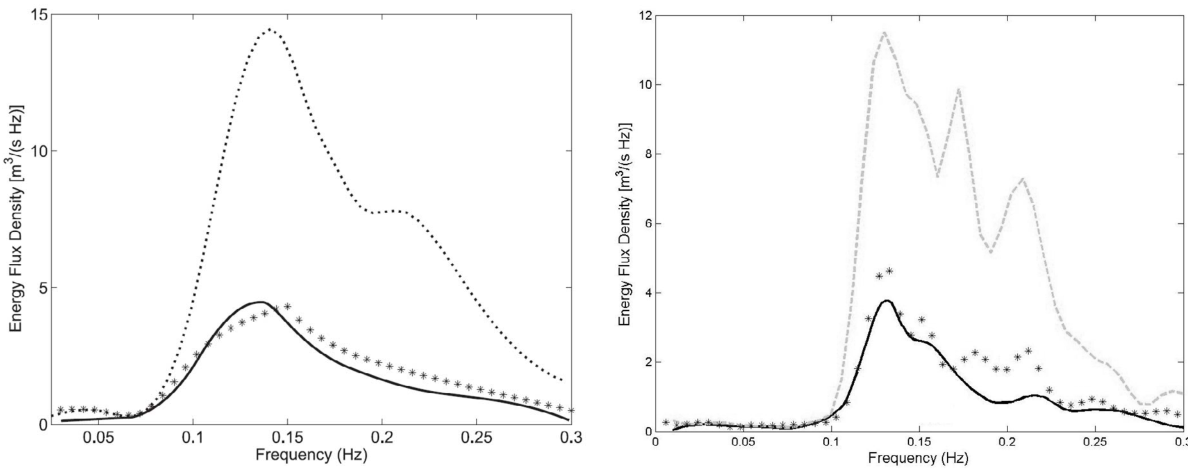


Figure 5. Vertical Profiles of A. backscattered intensity, B. high frequency R.M.S. vertical velocity normalized by free stream velocity, and C. wave band horizontal velocity. The red lines are from the period of maximum spatial attenuation rate (F_x/F, vertical line labeled B in figure 2), and the blue lines are from the period of maximum wave energy and maximum total dissipation ($F_{x,}$ vertical line labeled B in figure 2). Two layer model results for viscosities of 0.1(magenta), 0.01 (black), and 0.001 (green) are superimposed on the horizontal velocity plot (C) indicating the velocity during the period of maximum attenuation is best fit with a viscosity of 0.01 m^2/s .

Laboratory: Laboratory experiments in the shaker table tank and the wave tank continue, with kaolinite as the mud. We have completed a catalog of rheological measurements for a range of testing conditions, using a TA Instruments AR550—noting that shear thinning occurs with high shear stresses. Damping studies show that the damping coefficient is a function of lutocline thickness, as predicted, the wave steepness, and the wave frequency.

IMPACT/APPLICATIONS

The results of this combined field/laboratory/theory/modeling effort are field and lab data for model verification and testing and models for the propagation of water waves over regions of bottom mud. The dissipation due to a variety of mechanisms in included in the models; however, the most likely mechanisms will be determined from the field experiments. Laboratory experiments will provide data to elucidate the mechanisms of energy transfer from the waves to the sediment.



(a) (b)

Figure 6. Comparison of the prediction by phase-resolved simulations using BMWs and the Louisiana field measurement of Elgar and Raubenheimer (2008) on the evolution of wave spectra over a 2KM muddy bottom with the water depth varying from 4.5m to 2.5m. The comparisons are made with the measurements at: (a) 3:00am April 14, 2007; and (b) 7:00am April 14, 2007. The plotted lines are: the measured wave spectra at deeper water (dashed line) and shallower water (stars), and the simulated wave spectrum at shallower water (solid line). In the simulation, the measured wave spectrum at deeper water is used as the input.

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